LCA Methodology with Case Studies

Specifying Functional Units and Reference Flows for Comparable Alternatives

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Abstract

Goal, Scope, and Background. Despite documentation of product lifetime, performance, and system dependency issues, requirements for specifying functional units and reference flows in LCA have not been developed. The ISO standards simply note that selection between functions is dependent on the goals and scope of the study, that the functional unit must be clearly defined and measurable, and that the reference flows are the amount of product necessary per functional unit. The goal of this work is to suggest and demonstrate the use a set of requirements for specifying the functional unit and reference flows for comparative LCAs.

Methods. The suggested requirements were developed to address the lifetime, performance, and system dependency issues described in LCA literature and to ensure adequate information is available for the interpretation of results. Also, well developed methods for conceptual design were used to formulate aspects of the requirements to improve comparability of alternatives. A case study demonstrates the use of the requirements in materials selection for aircraft design. In the case study, functional units are specified for the component being designed and for the aircraft. Similarly, reference flows for the component, component interfaces, and the aircraft are quantified based on parametric and linear estimation models. Finally, an interpretation of data quality, uncertainty, assumptions, and limitations are presented.

Results and Discussion. The requirements are shown to be particularly important when the product be assessed operates as part of a larger system and when there are performance differences among alternatives. The case study illustrates the importance of including consideration of system and interface materials and energy flows in the comparison of aircraft components. Specifically, because the mass of interface materials is estimated as more than the difference in subsystem masses, differences in the variable mass of the aircraft and the lifetime fuel consumption are accounted for in the reference flows.

Conclusions. Some practitioners have recognized difficulties in accounting for product lifetime, performance, and system dependencies in LCA, even though a set of requirements has not been included in literature or in the ISO standards. The suggested requirements presented in this work were found to be useful in accounting for differences in materials and energy flows and in providing a transparent presentation, assessment, and interpretation of reference flows and ultimately in the LCA results.

Recommendations and Outlook. This work is significant because the specification of the functional unit and the definition of the reference flows dictate the materials and processes included in the LCA. Future work is needed to test the general applicability of the suggested requirements to a wide variety of product systems.

Keywords: Aircraft; comparable alternatives; functional unit; life cycle assessment (LCA); lightweight material selection; reference flow

Introduction

ISO14040 1997 (E) defines the functional unit as a measure of the performance of the functional outputs of a product system. Specification of the functional unit consists of the magnitude and duration of service, including the product's life span. The purpose of the functional unit is to provide a reference to which the inventory data are related to ensure alternatives are compared on a common basis. For each product system or alternative being assessed, the amount of product necessary per functional unit is known as the reference flow (International Standards Organization 1998). Definition of the reference flows must include the type and quantity of materials and energy linked to the functional unit and the number of times materials must be replaced during the analysis lifetime.

Because the reference material and energy flows dictate up and downstream process alternatives, definition of the functional unit and the reference flows are critical steps in LCA. In an ideal case, alternatives investigated in a study should fulfill the same technical function exactly during their quantifiable service lifetime (Günther and Langowski 1997). In reality, definition of the functional unit and reference flows can be difficult due to issues related to lifetime, performance, and system dependencies.

Specifically, Günther and Langowski (1997) cite two issues related to product lifetime: (1) consumer habits can influence product lifetime, and (2) the lifetime of the product is subject to nonsystematic variations. For example, product lifetime can be influenced by how often the customer uses the product (a.k.a. the duty cycle), by how harshly the customer uses the product, by the introduction of an alternative product with different or additional features, by the environment in which the product is used (wet, dry, salty, hot, cold, acidic, basic, etc.), by accidents, etc. The generation of reference flows for such lifetime differences was undertaken by McCleese and LaPuma (2002). In their LCA comparing internal combustion and electric vehicles, they analyze a range of distances traveled during the vehicle lifetime using Monte Carlo analysis.

Günther and Langowski also cite three performance issues related to the definition of the functional unit and reference flows: (1) consumer habits can influence product performance, (2) product alternatives ultimately offer functions/ features in addition to the function of interest, and (3) some functions/ features may or may not be directly related to quantitative performance indicators. Customer habits that

influence performance again include how often and harshly the customer uses the product and if the customer uses the product as anticipated/ instructed. As an example of the latter, in their LCI comparing ethylene glycol and propylene glycol antifreeze systems, Sauer and Franklin (1997) analyze the reference flows for not only functionally equivalent 'freezing point lowering' but also for a propylene glycol mixture in the proportions recommended for the more commonly used ethylene glycol.

Within the context of products with additional functions or features, Frischknecht (1997) notes that because the function of a product is rarely unidimensional, strict measurement of the primary function covers only a part (although the relevant one) of the comprehensive set of functions. Frischknecht suggests additional functions can be either assumed not to influence the modeling of the product system or subjected to an allocation procedure / boundary extension. Alternatively, Ruhland et al. (2000) (and the research presented here) develop mathematical models to relate multiple performance measures for multiple functions to reference flows.

Nonquantifiable functions are also a performance issue in the definition of functional units and reference flows. For example, in the comparison of paint systems (International Standards Organization 1997; Wenzel et al. 1997), the functional unit might be the 'unit surface protected when exposed to a certain environment for a specified time period' and 'nondripping, color, durability in closed container' are qualities that should also be considered. Functions that are difficult to quantify can be quantified through industry standards based on empirical performance. For example, nondripping paint is not a very precise term but can be quantified based on fluid properties or a simple test such as the rate that a paint runs down a standard inclined panel. Still, it is true that many properties may not be quantifiable or are difficult to evaluate.

For those difficult to quantify functions, Wenzel et al. (1997) conclude that a qualitative description must define a quality level for each function that facilitates comparison. Specifically, the service must be experienced as comparable by the user with respect to both the quantitative and qualitative characteristics. Unfortunately, Frischknecht (1997) also notes the boundary between quantifiable and nonquantifiable functions is not obvious and cannot objectively be drawn. Nevertheless Frischknecht and Wenzel et al. suggest all functions, quantitative and qualitative, should be reported within the definition of the functional unit and considered as additional technical information in the interpretation phase and related decision making processes.

In addition to lifetime and performance issues, system dependencies make the definition of functional units and reference flows difficult. Two aspects of system dependency can be defined: one relating to reference flow changes at the system level and one related to reference flow changes at subsystem interfaces. First, Wenzel et al. (1997) note that even if a given analysis is limited to looking at a product subsystem, in comparing alternatives the overall (or the system level) function must be the same. For example, if the mass of alternative vehicle components is different, then every extra kilogram is accompanied by an increase in power requirements (engine size, fuel consumption, etc.) all affecting the performance and costs (both initial and operational) of the vehicle. Second, even if a given analysis is limited to looking at a product subsystem, in comparing alternatives any changes in the balance of system materials must be included in the reference flows. For example, if aluminum washers are required to prevent corrosion between steel bolts and a magnesium plate, the washers should be included in the reference flows for a comparison of magnesium and aluminum plates (Reppe et al. 1998).

Despite documentation of lifetime, performance, and system dependency issues as described above, a systematic method for specifying functional units and reference flows has not been developed. ISO14040 (International Standards Association 1997) simply notes that selection between functions is dependent on the goals and scope of the study and that the functional unit must be clearly defined and measurable. Also, although Frischknecht (1997) falls short of providing a formal method, he suggests two ways to get started. First, Frischknecht suggests engaging a panel in which decision makers and stakeholders set the functional unit and the analyst defines and evaluates models adequate to the goals and functional unit defined. This option works well within the LCA methodology in that it will help ensure the inclusion of the concerns of stakeholders and facilitates early involvement of a peer review committee. Haas et al. (2000) provide an example in which the impact of agriculture on the environment is assessed. To facilitate the needs of multiple decision makers, multiple functional units were linked to specific agricultural and regional requirements in order to compare the impact of farms as well as farming intensity levels. As an example, CO_2 equivalents are presented per farm, per hectare, per livestock unit (each 500 kg live mass of cattle) and per product (ton milk).

The second method for specifying the functional unit and reference flows suggested by Frischknecht (1997) is to define the comparable functions in terms of what is accepted as comparable in the market place. For example, the functional unit could be defined on the basis of which products the consumer conceives as equivalent substitutes. For example, Wenzel et al. (1997) suggests customers might consider 20 inch and 22 inch color TVs to be comparable but might not consider black and white and color TVs to be comparable.

Although not captured in the published summary of their LCA, a more systematic approach for specifying the functional unit and reference flows was taken by Ruhland et al. (2000) in an analysis of cleaning processes. First, a definition of function was developed to capture multiple qualitative and quantitative characteristics of the service provided. This included consideration of issues important to cleaning process users and business managers. Next, qualitative descriptors and quantitative performance metrics were identified for the characteristics. Finally, an empirical process simulation model was used to relate all but one of the quantitative performance metrics to process material use and waste (the reference flows). The quantitative performance metric 'accepted remaining impurities per load' not considered in the model was used as a screening criteria (a thresh-

old) that all alternatives were required to meet. The qualitative performance descriptors (for part geometry, size, and material composition and for the quality of impurities removed from parts) were not integrated into the empirical model/ reference flows. Ruhland et al. stated that the qualitative parameters did not show a relevant influence on the material and energy flow within a certain range.

The method for specifying the functional unit and reference flows presented here formalizes and extends the basic process performed by Ruhland et al. (2000). The method includes consideration of issues related to lifetime, performance, and system dependencies. To demonstrate the use of the method, a material selection case study is presented comparing materials use in aircraft.

The objective of this work is to suggest and demonstrate the use of a set of requirements to guide LCA practitioners in the choice of the functional unit and the definition of the reference flows for comparative LCAs. The requirements are based on the findings of researchers described above and on the approach presented by Ruhland et al. (2000) in a way that (1) is applicable to any type of product system, (2) ensures comparability between alternatives, and (3) accounts for variations in subsystem and system lifetimes and performance. This work is unique in that no such requirements currently exist. Also, this work is significant because the choice of the functional unit and the definition of the reference flows are important topics that are often misunderstood and mismanaged to the detriment of many LCA studies.

1 Requirements for Specifying the Functional Unit and Reference Flows

Box 1 presents requirements suggested for specifying the functional unit and reference flows in comparative LCAs. These requirements were developed to address the lifetime, performance, and system dependency issues related to specifying the functional unit and reference flows in LCA cited above. Also, well developed methods for conceptual design (see Dieter, 2001 and Pahl and Beitz, 1996) were used to formulate aspects of the requirements to improve comparability. A discussion of each requirement follows.

1.1 Differentiation between the system and subsystem functions and solutions

In comparative LCA, it is critical that the product systems being compared perform the same function. When the subject of a comparative LCA is a part (a subsystem or component) of a larger system, it is the system level function that must remain constant. Also, system level material and energy flows that are dependent upon the composition or design of the subsystem must be included in the assessment (i.e., included in the reference flows). This is accomplished only when the functional unit reflects functions at the subsystem and systems levels.

As an example, whereas the system function for an automobile might be 'transporting goods,' subfunctions might include 'creating power,' 'transmitting power,' 'housing goods and occupants,' etc. In this example, if a LCA is comparing cockpit designs that 'house occupants,' a change in the amount of power needed to move the vehicle (within the subfunction 'creating power') that is dependent on the mass and aerodynamics of the cockpit should be included in the assessment. In this example, materials and energy flows associated with a larger (or smaller) power train would be included in the reference flows for the cockpit.

As a second example, whereas the system function for a house might be 'providing shelter,' subfunctions might include 'creating power,' 'maintaining a dry interior,' 'maintaining the interior temperature,' 'providing light and dark,' etc. In this second example, if a LCA is comparing materials for the walls of the house, a change in the heating requirements needed to 'maintain a certain interior temperature' as a function of the R value of each wall should be included in the assessment. Here, material and energy flows associated with a larger (or smaller) heating and air conditioning systems or the addition of insulation, etc. would be included in the reference flows.

Box 1: Suggested requirements for specifying the functional unit and reference flows in comparative LCAs

1. **Differentiation between the system and subsystem functions and solutions.** If the subject of the LCA is part of a larger system, a statement shall be provided differentiating between the system and subsystem functions. Each function should be presented as a task that is independent of any particular solution. At both the system and subsystem levels, a description of how solutions are consistent with the goal and scope of the study shall be included. Also, a description of the particular subsystem solutions to be assessed shall be included.

2. **Specification of the functional unit.** For the system and the subsystem of interest, a statement of the functional unit shall include 3 parts: (1) the magnitude of service, (2) the duration of service including the product's life span, and (3) the expected level of quality. Also, when comparing particular subsystem solutions, the functional unit should be the same at the systems level.

3. **Definition of the reference flows.** For the system and the subsystem of interest, definition of the reference flows shall include the type and quantity of materials and energy necessary per functional unit. At the system level, material and energy flows that change for subsystem alternatives should be included in the reference flows. At the subsystem level, any solution specific interface materials (materials used as finishes or in joining, securing, shielding, piping, conditioning equipment, etc.) should be included in the reference flows.

   Also, if the life of the subsystem is less than the duration specified in the functional unit, multiple subsystems should be included in the reference flows without artificially partitioning components (i.e., reference flows should not include ½ of a car but might include ½ of a kg of aluminum). Finally, if the life of subsystem exceeds the duration specified in the functional unit, the subsystem remaining at the end of life should be treated either as a coproduct or waste of the system during inventory analysis.

4. **Interpretation of the functional unit and reference flows.** For the system and the subsystem of interest, interpretation of the functional unit and reference flows shall include information needed for the analysis of data quality and uncertainty. Also, a discussion of assumptions and the limitations of the methods used should include an analysis of product features not included in the functional unit or the quantification of reference flows.

A functional decomposition as described by Pahl and Beitz (1996) and Dieter (2001) can be used to develop a detailed understanding of what the system and subsystems were expected to do. The overall function can be broken down into separate subfunctions (corresponding to subtasks) representing a change or transformation in the flow of energy or materials. Once the system and subsystem functions are identified, descriptions of the particular solutions to be assessed can be developed and used to specify system and subsystem functional units.

1.2 Specification of the functional unit

ISO14040 (International Standards Organization 1997) states that the purpose of the functional unit is to provide a reference to which the inventory data are related to ensure alternatives are compared on a common basis. Whereas the magnitude and duration of service are recognized as critical to the specification of the functional unit in LCA, less so is a description of the expected level of quality. Here, the level of quality captures characteristics that bear on the system or subsystem's ability to deliver the magnitude of service for the required duration and can dictate changes in reference flows.

As an example, a comparative LCA of automotive fuel tanks would differentiate between the subsystem function of 'storing energy' and the system function of 'transporting goods.' Whereas the magnitude and duration of service for the fuel tank might be 'MJ stored over 12 years' the expected level of quality might include 'without leaking.' Similarly, whereas the magnitude and duration of service for the automobile might be 'transport of a 136 kg payload 233,000 km over 12 years,' the expected level of quality might be 'while maintaining range, acceleration, and hill climbing capacity.' In this example, it is important to note that the expected level of quality dictates the system level reference flows. Specifically, the need to maintain vehicle acceleration, for example, requires increased power when the mass of the subsystem increases.

Assessment considerations and factors can be used to identify and characterize the magnitude and duration of service and the expected level of quality in specifying and interpreting the functional unit. Assessment considerations, like requirements used in product design, are a broad set of performance characteristics important to the analysis. Noting that designs must meet minimum performance thresholds before environmental considerations are made, assessment factors, like engineering characteristics used in product design, are qualitative descriptors and quantitative metrics related to each assessment consideration. Qualitative descriptors can aid in the comparison of features of the particular solutions without quantification. For example, understanding that one particular solution provides 'better, similar, or worse' performance in a specific area might be enough to support decision making. Quantitative metrics facilitate performance analysis, inventory analysis, and impact assessment and vary with different solutions / different reference flows. Once identified, assessment factors can be categorized as related to the magnitude and duration of the service or to quality and used to specify functional units and ultimately to quantify reference flows at the system and subsystem levels. Also, assessment factors can be used to understand what must remain constant (the functional unit should be the same at the systems level) and are a well recognized element of the life cycle engineering and life cycle design approaches that has a critical role in comparative LCA for design and any application of comparative LCA (Keoleian and Manery 1993, Design Center of Stuttgart 1991, Dermondy 1994).

1.3 Definition of the reference flows

Given the functional units, definition of the reference flows for the system and subsystem includes the type and quantity of materials and energy necessary per functional unit and are specific to subsystem solution being assessed. At the system level, flows that change for subsystem alternatives should be included in the reference flows. At the subsystem level, any solution specific interface materials (materials used as finishes or in joining, securing, shielding, piping, conditioning equipment, etc.) should also be included in the reference flows. As an example, the reference flows for a comparison of a steel and a HDPE gasoline fuel tank might include the tank, paint, straps, a shield, and related fasteners for both subsystems (Keoleian and Manerey 1997) and, because the steel tank weighs more than the HDPE tank, enhancements to the power train and the rest of the vehicle made from steel, iron, and aluminum, etc. and the fuel increment over the product life would be included at the systems level for the steel tank.

Definition of reference flows can be divided into the identification of flows and the quantification of flows. For the identification of flows, materials and energy to be included in the reference flows can be identified based on (1) the description of the particular solutions, (2) by successively asking if aspects of other subfunctions are solution dependent, and (3) by looking at interface issues (solution dependent materials and energy flows between the subsystem and system). Once all impacted subfunctions and interfaces are found, related changes in material and energy flows and transformations can be identified.

For the quantification of reference flows, three methods relate assessment factors to reference flows: (1) direct measurements based on prototype or manufactured products (products in hand), (2) use of a linear performance model(s), or (3) use of a parametric performance model(s). Direct measurement includes redesigning, building, and testing (to estimate the useful life) the subsystem and system of interest using each material and configuration option being considered. This allows materials and energy use (the reference flows) and the influence of change on assessment factors to be directly measured. Although this method ensures the accuracy of results at the subsystem and system levels, the method is far too time and resource intensive to be useful during product development and many other decision making situations.

Next, a linear model uses expert judgment of performance or published results of performance experiments to linearly relate alternative to assessment factors to reference flows. For example, Polmear (1996) suggests the substitution of aluminum for steel can save 40 to 50% of a part's mass. In a linear performance model, these substitution factors would

be applied to parts without any redesign or build. The advantage of such a linear performance model is that it requires very little information about the specific product being analyzed. The disadvantages are (1) that it may only be applied to situations for which data exist (2) that linear performance models are not expected to be as accurate as direct measurement in that they do not capture any nonlinearities, and (3) that it is difficult to determine if the data are representative of the population of interest.

A third way to relate assessment factors and reference flows is the use of parametric performance models as suggested by Ruhland et al. (2000). Specifically, mathematical relationships are used to capture linear and nonlinear material and energy use relationships for multiple assessment factors. Such parametric performance models can require more information and effort than a linear model and less information and effort than direct measurement. Like linear performance models, parametric performance models are not expected to be as accurate as direct measurement in that it is difficult to determine if the data are representative of the population of interest.

Finally, the life of the subsystem must be estimated and compared to the life of the system or the analysis lifetime. Failure modes and effects analysis and other reliability assessments (Dieter 2001) can be used to determine lifetime / replacement rates depending upon how the product is designed, how the customer uses the product, and the operating environment. Specifically, to obtain the lifetime specified in the functional unit, reference flows must reflect replacements, unless the life of the subsystem dictates the life of the product.

1.4 Interpretation of the functional unit and reference flows

Reference flows need to be subject to the same level of interpretation as all material and energy flows in the inventory analysis. Thus, any data quality assessment and analysis of data and model uncertainty applied to the inventory data are applied to the reference flows. For data quality ISO14040 (International Standards Organization, 1997) includes information for the assessment of time related coverage, geographic coverage, technology coverage, precision, completeness, and representativeness of the data, consistency and reproducibility of the methods used, and sources of data and their representativeness. For uncertainty, this includes information concerning uncertainties in data and in the results as described by Heijungs and Suh (2002). Also, a list and discussion of assumptions must include those related to data sources and methods used to quantifying of reference flows. Finally, a discussion of limitations includes those appropriate to inventory analysis and an analysis of product features not directly used in the quantification of reference flows (in other words, an analysis of the qualitative descriptors). The case study below illustrates the importance of interpretation in the specification of reference flows.

2 Case Study: Lightweight Material Selection for Aircraft

The reason for carrying out this case study was to help guide material selection in aircraft design towards reductions in material and other production costs; aircraft fuel consumption and emissions; life cycle material and chemical use and emissions; and life cycle global warming potential; and increases in the recyclability of materials in the aircraft.

2.1 Differentiation between the system and subsystem functions and solutions

As specified in Box 1, if the subject of the LCA is part of a larger system, a statement shall be provided differentiating between the system and subsystem functions. Here, the system is the aircraft and the function of the aircraft is 'to facilitate transport of a certain payload.' This overall function was decomposed into 4 subfunctions: house loads, provide power, provide lift, and facilitate landing. Similarly, the subsystem is a plate within the structure of the aircraft (and the system level function 'house loads') and the function is 'to provide only allowable deflection for a certain load within a certain design footprint.' Note that, except for specification that the component is a plate, each function is a task that is independent of any particular solution.

Also, a description of the particular subsystem solutions to be assessed shall be included in the differentiation between the system and subsystem functions and solutions. In this case, the *subsystem solutions to be assessed* are plates made from four materials: a wrought aluminum alloy, a cast aluminum alloy, an epoxy laminate carbon prepreg (a mixture of resin, curing agent, and reinforcement formed into sheets) composite, and a titanium / silicon carbide composite. No matter the material, each plate must fit within an area of 0.3 m^2 (with length of 0.5 m and width of 0.6 m) but can be as thick as needed.

The four material options are consistent with the goal and scope of the study because they are among the material choices available to designers in efforts to reduce operating fuel consumption and emissions through reductions in the mass and increases in the recyclability of the aircraft. The remainder of the components of the goal and scope were supported in the inventory analysis and impact assessment based on differences in the reference flows. Specifically, life cycle inventory flows included material and energy use throughout the life cycle with a focus on fuel consumption and emissions, chemicals use and emissions, the use of recyclable materials (in the aircraft and in manufacturing), and global warming gases. Also, the impact assessment included an activity-based production cost analysis including direct and hidden environmental costs, an analysis of the contribution to global warming, and an analysis of workplace hazards and pollution prevention opportunities (Henzi et al. 2001).

2.2 Specification of the functional unit

Again as specified in Box 1, for the system and the subsystem of interest, a statement of the functional unit shall include 3 parts: (1) the magnitude of service, (2) the duration of service including the product's life span, and (3) the expected level of quality. Similar to the approach used by Ruhland et al. (2000), a definition of function was developed to capture multiple qualitative and quantitative characteristics of the services provided. Related assessment con-

Table 1: Case study assessment consideration and factors

Assessment considerations	Assessment factors (units of measure)
The system should: • Facilitate transport of a certain payload a certain lifetime distance	**For the system:** • Magnitude of service: Mass of payload moved (kg) • Duration of service: Aircraft lifetime distance traveled (km/ 30 years) • Expected level of quality: Consistent operational requirements such as range (km/mission), speeds (km/hr), time on station, etc.
The subsystem should: • Provide only allowable deflection for a certain load within a certain design footprint over a certain lifetime	**For the subsystem:** • Magnitude of service: Component stiffness (N) • Duration of service: Component life (years) • Expected level of quality: The component must fit within a specified footprint (m^2 or m^3)

siderations and factors for each part of the functional unit were developed as listed in **Table 1**. Based on the assessment considerations, general statements of the system and subsystem functions were developed:

- The aircraft should facilitate transport of a specified payload over a specified lifetime while maintaining operating performance.
- The aluminum or composite plates should provide only allowable deflection for a certain load within a specified design footprint over a specified lifetime.

From these, more specific functional units incorporated the assessment factors:

- The functional unit for the aircraft was '20,455 kg payload moved over 30 years while maintaining range, radius, time on station, and speed.'
- The functional unit for the aluminum and composite plates was 'equivalent stiffness to aluminum within an area of 0.3 m^2 (with length of 0.5 m and width of 0.6 m) over 30 years.'

In turn, the reference flows for the subsystem were the mass of aluminum and composite needed to provide equivalent stiffness within the specified footprint, etc. and, for the system, the mass of aircraft materials (including fuel) needed to move the specified payload during the specified lifetime given the expected level of quality. Because this case study was a comparative analysis, the reference flows of interest were those that differ between the candidate component materials at the subsystem and system levels although the functional units should be the same.

2.3 Definition of reference flows

2.2.1 Identification of reference flows

Again as specified in Box 1, for the system and the subsystem of interest, definition of the reference flows began with identification of the type of materials and energy necessary per functional unit. At the subsystem level, the plate materials themselves are obvious parts of the reference flows. Also, any solution specific interface materials (materials used as finishes or in joining, securing, shielding, etc.) needed to be included in the reference flows. For the aluminum and composite plates, this includes finishing and joining materials. Finishing materials included a primer, sealer, and topcoat for the composite plates and, although the inventory analysis would need to include consideration of anodizing, the process does not add material to the reference flows for the aluminum plates. Joining materials to be included in the reference flows were identified by successively asking if the joining materials (mechanical fasteners, weld, adhesives, etc.) change dependent upon the component material being considered. It was assumed steel bolts would be used for the aluminum plates and adhesives are used to join composite plates to other components in the aircraft.

At the system level, material and energy flows that change for subsystem alternatives also needed to be included in the reference flows. For aircraft, if the mass of alternative components is different, then every extra kilogram is accompanied by an increase in wing area (in the 'lift' subfunction) and in thrust and fuel (in the 'provide power' subfunction) all affecting the performance and costs (both initial and operational) of the aircraft (Hale 1984). For example, the portion of the empty aircraft that varies with mass includes the wings, rotors (blades and heads), tail, landing gear, engine section / nacelle, air induct., propulsion, flight control, hydr./ pneu., and anti icing equipment groups. Because of this 'mass compounding,' it is for more than environmental reasons that mass may well be the most important aircraft design consideration. In fact, Hale suggests design experience has shown that the lowest mass design is also the lowest initial and operational cost.

2.2.2 Quantification of subsystem level reference flows

- **Analysis of subsystem performance and the expected level of quality**

As Young and Vanderburg account for differences in material properties in establishing reference flows for a hypothetical part (Young and Vanderburg 1994), aircraft designers use more or less aluminum or composite to compensate for differences in mechanical properties (e.g., different density, Young's Modulus, strength, etc.). In the case study, a parametric model was used to estimate the mass of aluminum and composite needed to support the same stiffness within the same footprint. The method, first reported by Henzi et al. (2001), is based on Ashby's (1999) material selection methodologies. Henzi et al.'s method estimates 'mass equivalents' or 'substitution factors' or the mass required to provide equivalent mechanical performance between a baseline material and a substitute for a certain configuration (e.g., a plate, shaft, beam, disk, etc.), the desired function (e.g., support a given type and magnitude load), and constraints (e.g., within a specified footprint, at a minimum deflection, etc.).

As an example for the case study, consider a 0.3 m² plate and assume the stiffness is specified. No matter the material used, the mass of the plate can be estimated as:

$$m = lwt\rho \qquad \text{(Eq. 1)}$$

where:

m = the mass of the plate (kg)
l = the length of the plate (=0.5 m)
w = the width of the plate (=0.6 m)
t = the thickness of the plate (m)
ρ = the density of the plate (kg/m³)

Also, the stiffness of the plate is given by:

$$S = C_1 \frac{EI}{w^2} = C_2 \frac{Elt^3}{w^2} \qquad \text{(Eq. 2)}$$

where:

S = the stiffness (N)
C = constants that depend on the distribution of the load
E = Young's Modulus (GPa)
I = the second moment of area (m⁴)

By combining Eqs. 1 and 2, a mathematical relationship relating component mass, the desired stiffness *S*, the footprint of the plate (*w* and *l*), and the various material properties for the plate is obtained:

$$m = w^{\frac{2}{3}} l^{\frac{5}{3}} \rho \left(\frac{S}{C_2 E} \right)^{\frac{1}{3}} \qquad \text{(Eq. 3)}$$

The 'mass equivalent' concept stems directly from this relationship. When comparing two materials, for example material *i* and a baseline material *b*, equivalent performance can be defined for identical values of *S*, *l*, *w*, and C_2. In this case study, the mass (or 'mass equivalent') of each material required to provide equivalent performance is:

$$m_i = w^{\frac{2}{3}} l^{\frac{5}{3}} \rho_i \left(\frac{S}{C_2 E_i} \right)^{\frac{1}{3}} \quad \text{and}$$

$$m_b = w^{\frac{2}{3}} l^{\frac{5}{3}} \rho_b \left(\frac{S}{C_2 E_b} \right)^{\frac{1}{3}} \qquad \text{(Eq. 4)}$$

Solving for performance constants and setting equal allows solving for the mass ratio as:

$$m_i = m_b \frac{\rho_i E_b^{\frac{1}{3}}}{\rho_b E_i^{\frac{1}{3}}} \qquad \text{(Eq. 5)}$$

Thus, Eq. 5 allows the mass of a functionally equivalent plate, m_i, to be estimated given the mass of the baseline plate, m_b, and the Young's Moduli and densities for each material if the stiffness, length, and width are specified. For this case study, if it is assumed wrought aluminum is the baseline plate with a mass of 10 kg, mass equivalents can be calculated for each alternative material using the material properties presented in **Table 2** and Eq. 5. The resulting mass equivalents for the case study plate are presented in **Table 3**. Thus, the mass equivalents are the reference flows (the mass of aluminum and composite material) for equivalent performance at the subsystem level as defined by the functional unit, less consideration of lifetime and interfaces.

- **Analysis of subsystem lifetime**

Also specified in Box 1, if the life of the subsystem is less than the duration specified in the functional unit, multiple subsystems should be included in the reference flows. In this case study, it was assumed that anodizing aluminum components and painting composite components is sufficient to ensure component lifetimes beyond the aircraft lifetime (i.e., no midlife replacement is necessary).

2.2.3 Quantification of system level reference flows

- **Analysis of system performance and the expected level of quality**

For quantification of system level reference flows, both system performance and the expected level of quality were captured simultaneously using a combination of parametric and linear models. The parametric model was based on guidance on aircraft mass estimation provided by the Society of Allied Weight Engineers (SAWE) (1996). The SAWE model was used to capture the impacts of mass compounding due to changes in the mass of the plates. First, the gross or total mass of the aircraft was divided into three parts:

Table 2: Material properties for case study (data from GRA00)

Material properties	Wrought aluminum alloy	Cast aluminum alloy	Epoxy laminate carbon prepreg	Titanium/silicon carbide composite
Density (ρ, Mg/m³)	2.7	2.8	1.5	3.9
Young's Modulus (E, GPa)	75	78	77.5	190
Shear Modulus (G, GPa)	28	30	28	73
Poisson's Ratio (ν)	0.34	0.34	0.38	0.22
Yield Strength (for metals) or Tensile Strength (for composites) (σ, MPa)	327	218	575	1175

Table 3: Mass equivalents for case study

Component	Wrought aluminum alloy (baseline)	Cast aluminum alloy	Epoxy laminate carbon prepreg	Titanium/ silicon carbide composite
Bent Plate: stiffness, length, width specified (as in Eq. 5)	10.0	10.2	5.5	10.8

$$M_g = M_{em} + M_{pl} + M_f \quad \text{(Eq. 6)}$$

where:

M_g = gross aircraft mass
M_{em} = empty aircraft mass
M_{pl} = payload mass
M_f = design fuel mass

Next, the empty aircraft mass M_{em} was divided into the portion impacted by mass compounding and the portion not impacted by mass compounding:

$$M_{em} = M_{cem} + M_{vem} \quad \text{(Eq. 7)}$$

where:

M_{cem} = constant portion of M_{em} that includes the auxiliary power plant; the fixed useful load; and the body, instruments, electrical, avionics, armament, furniture and related equipment, air conditioning, photographic, and load and handling groups

M_{vem} = variable portion of M_{em} that includes the wing, rotor (blades and heads), tail, landing gear, engine section/ nacelle, air induct., propulsion, flight control, hydr./ pneu., and anti icing equipment groups

Similarly, the design fuel mass M_f was divided into the mission portion and the reserve portion:

$$M_f = (1 + K_{rsv})M_{mf} \quad \text{(Eq. 8)}$$

where:

M_{mf} = mission fuel mass
K_{rsv} = reserve fuel factor

Finally, M_{vem} (the variable portion of M_{em}) was estimated as:

$$M_{vem} = K_{vem}M_g \quad \text{(Eq. 9)}$$

where:

K_{vem} = mass fraction for the variable portion of M_{em}

Assuming $\Delta M_{plate} = m_i - m_b$ (which is estimated from Eq. 5) and using Eqs. 6 to 9, the change in the gross aircraft mass was estimated as:

$$\Delta M_g = \Delta M_{vem} + \Delta M_{mf}(1 + K_{rsv}) + (\Delta M_{plate} + \Delta M_{fasteners}) \quad \text{(Eq. 10)}$$

Also, the change in the empty aircraft mass was estimated as[1]:

$$\Delta M_{vem} = K_{vem}\frac{(\Delta M_{plate} + \Delta M_{fasteners}) + \Delta M_{mf}(1 + K_{rsv})}{1 - K_{vem}} \quad \text{(Eq. 11)}$$

Finally, the change in the mission fuel mass was estimated as:

$$\Delta M_{mf} = \frac{\Delta M_g(1 - K_{vem}) - (\Delta M_{plate} + \Delta M_{fasmers})}{1 + K_{rsv}} \quad \text{(Eq. 12)}$$

Assuming M_{pl} = 20,455 kg, M_{cem} = 20,000 kg, K_{rsv} = 0.2, K_{vem} = 0.25, and M_{mf}/M_g = 0.24 allowed consistant performance at the systems level and Eqs. 10 to 12 to be solved for different values of $\Delta M_{plate} + \Delta M_{fasteners}$ for the alternative plate materials. Finally, the remainder of the reference flows for the aircraft were determined using a linear model assuming ΔM_{vem} is 80% aluminum, 10% steel, 5% titanium, and 5 % other materials as defined by the National Academy of Sciences (1993).

2.2.4 Summary of reference flows

The final set of reference flows for the first case study is presented in **Table 4**. The results of the component analysis include plate, finishing, and joining materials. The results of the aircraft analysis include aircraft materials and fuel consumption. As shown, although only the full LCA reveals the full impacts of the differences in the reference flows, the lifetime fuel consumption is least for the composite plates.

[1] Note that although DM_{vem} does not include DM_{comp}, it is based upon the value of DM_{comp}.

Table 4: Reference flows for functionally equivalent aircraft plates

Material	Anodized wrought aluminum alloy	Anodized cast aluminum alloy	Painted epoxy laminate carbon prepreg	Painted titanium/ silicon carbide composite
Plate Materials				
Wrought aluminum alloy (kg)	10.0			
Cast aluminum alloy (kg)		10.2		
Epoxy laminate carbon prepreg (kg)			5.5	
Titanium/silicon carbide composite (kg)				10.8
Finishing Materials				
Primer, sealer, topcoat (kg, 0.001 m thick covering the total surface of the plate)	none on part	none on part	1.1E-3	1.1E-3
Joining Materials				
Steel bolts (kg, 20 pieces at 15 g each at 0.02 m centers along both 0.2 m stretches of the plate)	3	3		
Adhesive (kg, at 0.001 m thick covering one half plane of the plate)			3.2E-6	3.2E-6
Total plate, finishing, and joining materials (kg)	**13.0**	**13.2**	**5.5**	**10.8**
ΔAircraft Materials (kg per trip, = % composition x ΔM_{vem})				
Aluminum		6.6E-2	–3.2	–9.5E-1
Steel		8.3E-3	–4.0E-1	–1.2E-1
Titanium		4.1E-3	–2.0E-1	–5.9E-2
Other materials		4.1E-3	–2.0E-1	–5.9E-2
ΔLifetime Fuel (kg/ 30 years at 300 missions/ year)				
Jet fuel		701	–33,960	–10,060

2.4 Interpretation of the functional unit and reference flows

2.4.1 Data Quality Information

The data and models used in the case study are publicly available. This was intended to facilitate demonstration of the suggested requirements for defining functional units and reference flows. That stated, data quality for the case study is described as follows:

- Time related coverage: It is expected that the mathematical relationships developed by the SAWE are representative of current aircraft technology.
- Geographic coverage: Geographic specificity has not been considered in the development of the reference flows.
- Technology coverage: For the subsystem, the component being designed is a 0.5 x 0.6 m plate with the stiffness is specified. The baseline design is made from anodized wrought aluminum at a mass of 10 kg. Alternative plate designs are an anodized cast aluminum plate, a painted epoxy laminate carbon prepreg composite plate and a painted titanium / silicon carbide composite plate. Steel bolts are used for the aluminum plates and adhesives are used to join composite plates to other components in the aircraft. For the system, the aircraft is a turbojet at a baseline gross aircraft mass of 86,745 kg that will carry a payload of 20,455 kg.
- Precision, completeness, and representativeness of the data: It is expected that the mathematical relationships developed by the SAWE apply to conceptual aircraft design (when the exact materials have yet to be selected). Additional relationships provided by SAWE and not applied here can be used to refine all estimates.
- Sources of data and their representativeness: Although primary data from the Boeing Company was used in the related LCA, no primary data has been included here. Instead, all data presented here are publicly available to facilitate demonstration of the suggested requirements for defining functional units and reference flows.
- Consistency and reproducibility of the methods used: The methods used are based on sound engineering principles captured by the linear and parametric models used. Because all models and data used are publicly available, the analysis is reproducible. The models have, however, not been validated for this application.

2.4.2 Uncertainty Information

In the case study, sources of subsystem data and model uncertainty are variations in material properties, loads, and factors of safety. Sources of system data and model uncertainty include variations in payload, empty aircraft mass, the definition and percent of the variable portion of the aircraft's empty mass, methods for the estimation of the composition of the additional aircraft materials, fuel consumption, and in the relations presented in Eqs. 6 to12. Analysis of these sources of uncertainty in these data and models is planned for future research.

2.4.3 Analysis of product features not included in the functional unit or the quantification of reference flows

Qualitative descriptors for product features not captured in the mass equivalents model for each plate are listed in **Table 5**. As shown, each material was evaluated on a three point scale as compared to the baseline. Specifically, materials were rated as 'better than the baseline' (designated with a '+'), 'similar to the baseline' (designated with an 'S'), and 'worse than the baseline (designated with a '–'). In addition to the LCA results based on the quantitative assessment factors, the results of the analysis of the qualitative descriptors should be considered in decision making.

2.4.4 Discussion of Assumptions and Limitations

Assumptions related to data sources and methods used to quantifying of reference flows were:

- For the quantification of subsystem reference flows:
  - It has been assumed that design issues not considered by the mass equivalents model do not dominate material selection. Many other design issues beyond the structural design factors considered in the mass equivalents model are typically important in guiding the design process.
  - It has also been assumed that anodizing aluminum plates and painting composite plates is sufficient to ensure component lifetimes beyond the aircraft lifetime (i.e., no midlife replacement is necessary). Thus, an anodized aluminum plate and a painted composite plate are included in the reference flows. Also, although the exact failure mechanism for components can vary,

Table 5: Product Features not captured in subsystem performance (based on information from Granta Design (2000))

Material	Recycled fraction	Flammability	Protection from Fresh Water	Protection from Organic Solvents	Protection from Sea Water	Protection from Strong Acid	Protection from Strong Alkalis	Protection from UV	Protection from Wear	Protection from Weak Acids	Protection from Weak Alkalis
Wrought aluminum alloy	BASELINE										
Cast aluminum alloy	S	S	S	S	S	S	S	S	S	S	S
Epoxy laminate carbon prepreg	–	–	S	–	S	–	+	–	S	S	S
Titanium/silicon carbide composite	–	+	S	S	+	–	+	S	+	S	+

common classes of failure modes for aluminum and composite components are mechanical, chemical, thermal, and joint failures. Aluminum components are also subject to mixed mode failures related to corrosion and fatigue. Composite components are also subject to scission or cross linking due to radiation (Henzi et al. 2001).
  - Because it was assumed that the aluminum and composite components would last the life of the aircraft, no system expansion or allocation of coproducts is required for the inventory analysis.

- For the quantification of system reference flows:
  - It has been assumed that the turbojet in the example will carry a payload (M_{pl}) of 20,455 kg and the constant portion of the empty aircraft mass (M_{cem}) is 20,000 kg. The empty aircraft mass is based on a thrust to weight ratio of 0.28, a thrust to engine ratio of 5, and a structural weight fraction of 0.425 (Hale 1984).
  - It has been assumed that the mass fraction for the variable portion of the empty aircraft mass (K_{vem}) is 0.25 as recommended by the Society of Allied Weight Engineers (1996). It has also been assumed that the variable portion of the aircraft mass varies linearly with the gross mass and that any increase can be represented by an even distribution of 80% aluminum, 10% steel, 5% titanium, and 5% other materials (National Academy of Sciences 1993).
  - It has been assumed that the ratio of the mission fuel mass to the gross aircraft mass (M_{mf}/M_g) is 0.24 and the reserve fuel factor (K_{rsv}) is 0.2. Also, climb versus cruise fuel requirements and emissions are very different for different aircraft types. Although the linear assumption applied here may not be accurate within the context of aircraft design, it is useful in comparing materials use in LCA. Other methods for estimating fuel use are provided by the Federal Aviation Administration data (Federal Aviation Administration 1998).

Limitations of the case study also stem from the use of data and models that are publicly available and have not been validated for the case study parameters presented. Again the presentation here was intended to facilitate demonstration of the suggested requirements. That stated, specific limitations for the case study are:

- **Related to the use of the mass equivalents method.** Again, Frischknecht (1997) notes that because the function of a product is rarely one dimensional, strict measurement of the function covers only a part (although the relevant one) of the comprehensive set of functions. Mass equivalents are essentially mathematical models to relate multiple performance measures for some, *but not all*, functions to reference flows. Some of the remaining functions are qualitatively assessed in the interpretation.

  Specifically, for each plate design, the product features not included in the mass equivalents model were captured with qualitative descriptors. The summary of reference flows in Table 4 lists the epoxy carbon composite as the design with, for example, the smallest aircraft fuel consumption. At the same time, based on the information presented in Table 5, the epoxy carbon composite is inferior to the aluminum plates in the areas of recycled fraction, flammability, and protection from organic solvents, strong acids, and UV. Also, the epoxy carbon composite provides superior protection to strong alkalis. Thus, estimation of the reference flow without consideration of these qualities is a limitation.

- **Related to assumptions of linearity in the SAWE Model.** The Society of Allied Weight Engineers (1997) notes that the categorization of systems into constant and variable mass portions is approximate as each of the variable mass does not vary linearly with the gross aircraft mass. Also, because an increase in the aircraft mass requires a different proportional changes in wing area and tail volume, if these materials are not evenly distributed throughout the aircraft they will not scale in this same proportion. Still, aluminum will dominate these changes.

3 Discussion

The case study presented here demonstrates the use of the suggested requirements for specifying functional units and reference flows in comparative LCAs. Within the requirements, specification functional units and reference flows was preceded by the differentiation between system and subsystem functions and solutions and followed by an interpretation of data quality, uncertainty, assumptions, and limitations of the data collection and estimation methods used. Ultimately, the case study used a combination of parametric and linear models to estimate reference flows.

For each plate design, the functional unit was 'equivalent stiffness to aluminum within an area of 0.3 m^2 (with length of 0.5 m and width of 0.6 m) over 30 years.' This functional unit quantified the magnitude of service for a life equivalent to the life of the system but left the expected level of quality to decision tradeoffs highlighted in the interpretation. Subsequently, identification and quantification of the reference flows for this subsystem was based on finishing and interface materials and plate materials estimated using the mass equivalents method.

More generally, the 'mass equivalents' or 'substitution factor' method provides a way to assess relationships between component performance and reference flows that moves beyond comparing equal masses of different materials in LCA. The method can be applied to other component classes producing similar results (the results for 9 classes of components are shown in **Table 6**). Basically, the method provides a means of estimating material substitution factors.

As a means of validating this application of the mass equivalents method, the Society of Allied Weight Engineers (1996) provides a distribution of weight reduction for 40 structural aircraft components. They found that for the components studied, mass reductions attained by advanced composites were between 11 and 47% with a reduction of 20 to 30% being most frequent. From Table 6, the average reduction presented

Table 6: Mass equivalents for case study

Component class	Performance relationships (modified from Ashby, 1999)	Wrought aluminum alloy (baseline)	Cast aluminum alloy	Epoxy laminate carbon prepreg	Titanium/ silicon carbide composite
Bent Plate: stiffness, length, width specified (the case study plate) Buckled Plate: load, length, width specified	$m_i = m_b \dfrac{\rho_i E_b^{\frac{1}{3}}}{\rho_b E_i^{\frac{1}{3}}}$ as in Equation 5	1	1.02	0.55	1.08
Tensile Tie: stiffness, length specified Bent Beam: stiffness, length, height specified Compressed Column stiffness, length specified Pressurized Cylinder: distortion, pressure, radius specified	$m_i = m_b \dfrac{\rho_i E_b}{\rho_b E_i}$	1	0.99	0.54	0.58
Twisted Shaft: stiffness, length, shape specified (where: G_i is the shear modulus of material I and G_b is the shear modulus of material b)	$m_i = m_b \dfrac{\rho_i G_b^{\frac{1}{2}}}{\rho_b G_i^{\frac{1}{2}}}$	1	1.00	0.56	0.91
Twisted Shaft: stiffness, length, wall thick specified	$m_i = m_b \dfrac{\rho_i G_b^{\frac{1}{3}}}{\rho_b G_i^{\frac{1}{3}}}$	1	1.01	0.55	1.07
Bent Beam: stiffness, length, shape specified Buckled Column: load, length, shape specified	$m_i = m_b \dfrac{\rho_i E_b^{\frac{1}{2}}}{\rho_b E_i^{\frac{1}{2}}}$	1	1.01	0.55	0.92
Pressurized Sphere: distortion, pressure, radius specified (where: v_i is the Poisson's ratio of material I and v_b is the Poisson's ratio of material b)	$m_i = m_b \dfrac{\rho_i (1 - v_i) E_b}{\rho_b (1 - v_b) E_i}$	1	0.99	0.51	0.69
Tensile Tie: strength, length specified Twisted Shaft: load, length, outer radius specified Bent Beam: load, length, height specified Compressed Column load, length, shape specified Pressurized Cylinder: distortion, pressure, radius specified Pressurized Sphere: Distortion, pressure, radius specified Rotating Disk: Max energy/mass, no failure (where: ρ_i is the failure strength of material I and σ_b is the failure strength of material b)	$m_i = m_b \dfrac{\rho_i \sigma_b}{\rho_b \sigma_i}$	1	1.55	0.32	0.41
Twisted Shaft: load, length, shape specified Bent Beam: load, length, shape specified	$m_i = m_b \dfrac{\rho_i \sigma_b^{\frac{2}{3}}}{\rho_b \sigma_i^{\frac{21}{3}}}$	1	1.35	0.38	0.63
Twisted Shaft: load, length, wall thick specified Bent Beam: load, length, width specified Bent Plate: strength, length, width specified Buckled Plate: load, length, width specified	$m_i = m_b \dfrac{\rho_i \sigma_b^{\frac{1}{2}}}{\rho_b \sigma_i^{\frac{1}{2}}}$	1	1.26	0.42	0.78
Any component in which material substitution is based on a constant component volume	$m_i = \dfrac{\rho_i}{\rho_b} m_b$	1	1.03	0.56	1.47

is 37% with a maximum reduction of 68%. Specifically, for the epoxy composite, 3 of the mass equivalent reductions exceed those studied by SAWE, most are at the high reductions end of the distribution, and all offer an improvement over wrought aluminum. For the titanium/silicon carbide composite, again some of the mass equivalent reductions exceed those studied by SAWE but not all offer an improvement over wrought aluminum (titanium is shown not to be an improvement for bent and buckled plates, twisted shafts, and constant volume substitutions). Thus, it appears either the mass equivalents method over estimates reductions, the linear model does not represent the breadth of components considered by the mass equivalents method, or design issues not considered by the mass equivalents model dominate material selection.

Table 7: Analysis of the suggested requirements for specifying functional units and reference flows

	How managed in the suggested requirements and case study	Opportunities for additional research
Lifetime issues		
(1) Consumer habits can influence product lifetime	Not explicitly considered (although product failure is captured in qualitative descriptors)	Provide a method to capture the influence of consumer habits on product lifetime
(2) The lifetime of the product is subject to nonsystematic variations		Provide a method to capture the influence of nonsystematic lifetime variations (consider the use of Monte Carlo analysis as suggested by McCleese 2002)
Lifetime issues in general		Incorporate failure analysis and lifetime estimation methods
Performance issues		
(1) Consumer habits can influence product performance	Not considered	Provide a method to capture the influence of consumer habits on product performance
(2) Product alternatives ultimately offer functions/ features in addition to the function of interest	Functional units and reference flows consider multiple features related through parametric models	Provide further insight into how to model multiple features including which features need to be considered, how to understand data quality and uncertainty, etc.
(3) Some functions/ features may or may not be directly related to quantitative performance indicators	Qualitative descriptors are used in the interpretation and in decision making related to LCA results	Provide further insight into the use of qualitative descriptors in interpretation and decision making
System dependency issues		
(1) In comparing alternatives, the system function must be the same	Parametric models (for mass compounding in the case study) capture changes in assembly materials and energy flows to maintain performance at the systems level	Illustrate how system performance impacts systems other than aircraft. For example: • Other transportation systems • In a PC, as the processing speed increases, do the cooling and power supply system need to be augmented? • Is the nutritional value of food impacted by the use of pesticides? • Does the addition of insulation to a house allow smaller heating and air conditioning systems to be used?
(2) In comparing alternatives, any changes in the balance of system materials must be included in the reference flows	Changes in materials beyond the subsystem of interest are identified through evaluation of assembly materials	Provide a method to identify what materials must be included and what can be ignored

In addition to the different plate masses that resulted from the application of the mass equivalents method in the case study, changes in interface materials had a large role in the magnitude of the final set of reference flows. Noting that in some cases, the assembly materials (from mass compounding) and fasteners may be under the cut off rule assigned in inventory analysis, in other cases, the differences will be quite important. Using the information in Table 4 as an example, a titanium / silicon carbide composite plate that has a mass 0.8 kg greater than the aluminum baseline, has a mass that is 2.2 kg less than the baseline when interface materials are also considered. For the reference flows, this difference resulted in substantially less fuel use, aluminum, steel, titanium and other aircraft materials for the a titanium / silicon carbide composite option.

Table 7 compares the suggested requirements to the lifetime, performance and system dependency issues identified in the introduction. As shown, opportunities for additional research relate to modeling product lifetime, the influence of customer habits, the role of qualitative information in decision making, uncertainty and data quality in performance modeling, and application to other product systems.

Finally, to ensure consistency with the goal and scope of the study as noted in ISO14041, the differentiation between the system and subsystem functions and solutions includes a description of how solutions are consistent with the goal and scope of the study. Such considerations have two advantages: (1) the practitioner is encouraged to look at the system and the subsystem within the context of the goal and scope before substantial resources are expended on the assessment and (2) assessment considerations can be developed with the goal and scope of the study in mind. In an alternative approach, Ruhland et al. (2000) incorporated the goal of the assessment into the statement of the function. Similarly, in the case study presented here, the functions might be stated as:

- The aircraft should facilitate transport of a specified payload over a specified lifetime while maintaining operating performance (range, radius, time on station, speed, etc.) and reducing material and production costs; fuel consumption and emissions; and life cycle material and chemical use, emissions, and contribution to global warming.
- The aluminum or composite components should provide only allowable deflection for a certain load within a speci-

fied design footprint over a specified lifetime while decreasing the mass and increasing the percent recyclable.

Here, adding reference to the study goals within the functional unit becomes burdensome. As such, for the requirements suggested here, inclusion of a description of how solutions are consistent with the goal and scope of the study is considered to be consistent with the standard.

In conclusion, the functional unit and the reference flows dictate up and downstream process alternatives and therefore are critical steps in LCA. Some practitioners have recognized difficulties related accounting for lifetime, performance, and system dependencies in LCA, even though a set of requirements has not been included in literature or in the ISO standards. This work suggests such requirements and provides a single case study to demonstrate their importance. Future work is needed to test the general applicability of these requirements to a wide variety of product systems. The ultimate goal is a set of requirements that aid practitioners in providing a transparent presentation, assessment, and interpretation of LCA results.

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Functional Equivalence of Industrial Metal Cleaning Processes: Comparison of Metal Cleaning Processes Within LCA

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In an LCA case study, the three most frequent industrial metal cleaning technologies were assessed: Cleaning based on aqueous cleaning agents, non-halogenated hydrocarbon solvents and halogenated hydrocarbon solvents. Beside optimisation analysis, the comparison of the cleaning processes was a main goal of the study. The function of metal cleaning processes can be described with a set of parameters called functional parameters. In order to compare different cleaning processes within LCA, it is a precondition that all relevant functional parameters be equivalent. However, metal cleaning processes from different companies normally differ in most of the functional parameters and, thus, are not functionally equivalent. Therefore, it is necessary to calculate the material and energy flows of the processes corresponding to a reference function as a basis for comparison. This can be achieved by simulating the processes according to the functional parameters with the help of a process model. For a general comparison of the technologies, it is also necessary to consider the assessed machines having the same level of optimisation and the same scale.